# CPT violation and $B$-meson oscillations

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Recent evidence for anomalous CP violation in $B$-meson oscillations can be interpreted as resulting from CPT violation. This yields the first sensitivity to CPT violation in the $B_s^0$ system, with the relevant coefficient for CPT violation constrained at the level of parts in $10^{12}$.



Experimental studies of spacetime symmetries involving the discrete transformations under charge conjugation C, parity inversion P, time reversal T, and their products CP and CPT have played a major role in establishing the Standard Model (SM) of particle physics. All these symmetries are known to be broken except CPT, and their description in terms of the SM has been in excellent agreement with laboratory experiments. Among the most powerful tools available for investigations of these symmetries are the neutral-meson systems, in which particles and antiparticles mix interferometrically and thereby offer high sensitivity to deviations from exact symmetry.

The D0 Collaboration has recently presented data supporting an anomalous like-sign dimuon charge asymmetry in $B$-meson mixing [1, 2], interpreting it as evidence for CPT-invariant CP violation beyond the SM. Here, we show that this anomalous asymmetry could also arise from T-invariant CP violation in $B_s^0$-$\overline{B}_s^0$ mixing. A CPT-violating effect in $B$-meson mixing was predicted some time ago [3] as potentially arising from spontaneous breaking of Lorentz symmetry in an underlying unified theory [4], and the usual requirement of CPT-invariant CP violation for baryogenesis [5] can be evaded in this context [6]. The $B_s^0$-$\overline{B}_s^0$ system is of particular interest for studies of CPT violation because several complete particle-antiparticle oscillations occur within a meson lifetime [7]. As part of the analysis here, we show that the anomalous like-sign dimuon charge asymmetry offers sensitivity to CPT breaking, and we use this asymmetry to obtain the first quantitative measure of CPT violation in the $B_s^0$-$\overline{B}_s^0$ system.

An appropriate framework for investigating CPT violation in neutral mesons is effective field theory. In this context, CPT violation is necessarily accompanied by Lorentz violation [8]. We can therefore work here within the comprehensive effective field theory describing general Lorentz violation at attainable energies known as the Standard-Model Extension (SME) [9]. Each CPT-violating term in the SME Lagrange density is the product of a CPT-violating operator and a controlling coefficient. The SME contains both the SM and General Relativity, so it serves as a realistic theory for analyzing experimental data for signals of CPT violation. Several SME-based searches for CPT violation with neutral-meson oscillations [10–13] and numerous investigations using a wide variety of other physical systems [14] have been performed over the past decade.

The analysis of meson mixing in the SME context reveals the four neutral-meson systems $K^0$-$\overline{K}^0$, $D^0$-$\overline{D}^0$, $B_d^0$-$\overline{B}_d^0$, and $B_s^0$-$\overline{B}_s^0$ contain a total of 16 independent observables for CPT violation [15]. The corresponding 16 combinations of SME coefficients are conventionally denoted as $(\Delta a^K)_\mu$, $(\Delta a^D)_\mu$, $(\Delta a^{B_d})_\mu$, $(\Delta a^{B_s})_\mu$. These coefficients are known to be observable only in flavor-changing experiments with neutral mesons or neutrinos [16] and in gravitational experiments [17]. Several experimental searches have yielded high sensitivities to certain components of $(\Delta a^K)_\mu$, $(\Delta a^D)_\mu$, and $(\Delta a^{B_d})_\mu$ [10–13]. In this work, we report the first sensitivity to the coefficient $(\Delta a^{B_s})_\mu$. We also outline a procedure that could improve on this result using the full D0 dataset.

The D0 Collaboration measures the dimuon charge asymmetry

$$A_{\rm sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \tag{1}$$

where $N_b^{++}$ and $N_b^{--}$ represent the number of events in which two $b$ hadrons decay semileptonically into two positive muons and two negative muons, respectively. One measurement of this asymmetry is obtained by correcting the raw like-sign dimuon sample for various backgrounds, yielding [2]

$$A_{\rm sl}^b = -0.00736 \pm 0.00266 \pm 0.00305, \tag{2}$$

where the first error is statistical and the second systematic. Combining in quadrature yields an effect at 1.8 standard deviations. The D0 Collaboration also studies the inclusive ‘wrong-charge’ muon charge asymmetry $a_{\rm sl}^b$ of semileptonic decays of $b$ hadrons to muons with charge opposite to that of the original $b$ quark,

$$a_{\rm sl}^b = \frac{\Gamma(\overline{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\overline{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)}. \tag{3}$$

This asymmetry is a measure of CPT-invariant CP violation and hence of T violation. Assuming CPT symmetry holds and under other mild assumptions such as no direct CP violation, it can be shown that $A_{\rm sl}^b = a_{\rm sl}^b$ [18], which enables a second measurement of $A_{\rm sl}^b$. This second measurement is consistent with no effect at 0.4 standard deviations. The final D0 result for $A_{\rm sl}^b$ is obtained by combining the two measurements to minimize systematic uncertainties. It reveals a signal 3.2 standard deviations

away from the SM prediction for CPT-preserving T violation, which is [2, 19]

$$A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}. \tag{4}$$

For our present purposes, the second measurement using the asymmetry (3) and the combined measurement both turn out to be irrelevant, so only the first result (2) for $A^b_{\rm sl}$ is involved in the analysis that follows.

In this work, we allow for T-invariant CP violation in $B^0_s$-$\overline{B}^0_s$ oscillations. A measure of this CPT violation is given by the inclusive 'right-charge' muon charge asymmetry $\mathcal{A}^b_{\rm CPT}$ of semileptonic decays of $b$ hadrons to muons with the same charge as that of the original $b$ quark,

$$\mathcal{A}^b_{\rm CPT} = \frac{\Gamma(\overline{B} \to \mu^- X) - \Gamma(B \to \mu^+ X)}{\Gamma(\overline{B} \to \mu^- X) + \Gamma(B \to \mu^+ X)}. \tag{5}$$

In terms of this CPT asymmetry and the T asymmetry (3), we find the dimuon charge asymmetry $A^b_{\rm sl}$ of Eq. (1) can be written in the nested form

$$A^b_{\rm sl} = \frac{\left(\dfrac{1+a^b_{\rm sl}}{1-a^b_{\rm sl}} - \dfrac{1+\mathcal{A}^b_{\rm CPT}}{1-\mathcal{A}^b_{\rm CPT}}\right)}{\left(\dfrac{1+a^b_{\rm sl}}{1-a^b_{\rm sl}} + \dfrac{1+\mathcal{A}^b_{\rm CPT}}{1-\mathcal{A}^b_{\rm CPT}}\right)} \approx a^b_{\rm sl} - \mathcal{A}^b_{\rm CPT}, \tag{6}$$

where the last expression assumes small T and CPT violation at first order in the asymmetries. This expression reveals that the dimuon charge asymmetry $A^b_{\rm sl}$ is sensitive to CPT violation as well as T violation. In what follows, the result (6) is used to obtain the first quantitative measure of CPT violation in the $B^0_s$-$\overline{B}^0_s$ system.

For definiteness, we assume the only source of T violation is the SM contribution $a^b_{\rm sl}({\rm SM}) = A^b_{\rm sl}({\rm SM})$ given by Eq. (4). Combining with the D0 dimuon asymmetry (2) yields the value

$$\mathcal{A}^b_{\rm CPT} = 0.00713 \pm 0.00405, \tag{7}$$

where the D0 statistical and systematic errors are combined in quadrature. Our goal is to interpret this result as a measure of CPT violation in $B$-meson mixing, and in particular in the $B^0_s$-$\overline{B}^0_s$ system.

In general, oscillations of neutral mesons are governed by a $2 \times 2$ effective hamiltonian $\Lambda$ [20]. The CPT-violating contributions to $\Lambda$ are controlled by the difference $\Delta\Lambda = \Lambda_{11} - \Lambda_{22}$ of the diagonal terms of $\Lambda$, while the off-diagonal terms govern T violation. The size of CPT violation is unknown *a priori.* We adopt here the $w\xi$ formalism for $\Lambda$ [15], which is independent of phase conventions and allows for CPT violation of arbitrary size. In this formalism, CPT violation is governed by a complex parameter $\xi$ of any magnitude, and $\Delta\Lambda = -(\Delta m + \frac{1}{2} i \Delta\Gamma)\xi$. For the $B^0_s$-$\overline{B}^0_s$ system, $\Delta m \equiv \Delta m_s = m_H - m_L$ is the mass difference between the heavy and light eigenstates, $\Delta\Gamma \equiv \Delta\Gamma_s = \Gamma_L - \Gamma_H$ is their width difference, and the parameter for CPT violation is denoted $\xi_s$. We also adopt the standard notation $x_s = \Delta m_s/\Gamma_s$, $y_s = \Delta\Gamma_s/2\Gamma_s$, $2\Gamma_s = \Gamma_L + \Gamma_H$.

Since CPT violation comes with Lorentz violation [8], the complex parameter $\xi$ cannot be a scalar. Instead, it must depend on the meson 4-momentum and is therefore a frame-dependent quantity. For example, the rotation of the Earth relative to the constant vector $\Delta\vec{a}$ typically generates a variation with sidereal time in $\xi$ [21]. The canonical frame used in studies of CPT and Lorentz violation is the Sun-centered frame with coordinates $(T, X, Y, Z)$ [22]. In this frame, the CPT-violating parameter $\xi \equiv \xi(T, \vec{p}, \Delta a_\mu)$ is a function of sidereal time $T$, meson 4-momentum $(E(\vec{p}), \vec{p})$, and the four constant SME coefficients $\Delta a_\mu$ for CPT violation for the given meson system. The explicit functional form of $\xi$ can be found using perturbation theory for the SME and is given as Eq. (14) of Ref. [15]. Hermiticity of the Lagrange density ensures the reality of $\Delta\Lambda$, which for the $B^0_s$-$\overline{B}^0_s$ system implies the condition $y_s {\rm Re}\,\xi_s + x_s {\rm Im}\,\xi_s = 0$.

For our present purposes, it suffices to average over the sidereal time and the meson 4-momentum spectrum. Since the particle distributions from $b$-hadron decay for the Fermilab collider are symmetric in local detector polar coordinates for D0, the dependence on spatial components $(\Delta a^{B_s})_J$ cancels through this procedure. We obtain the averaged value

$$\overline{{\rm Im}\,\xi_s} = \frac{y_s}{x_s^2 + y_s^2} \frac{\overline{\gamma}(\Delta a^{B_s})_T}{\Gamma_s}, \tag{8}$$

where $\overline{\gamma} \simeq 4.1$ is the mean gamma boost factor for the $B^0_s$ mesons in the D0 experiment.

Given the result (8), we can extract a measurement of $(\Delta a^{B_s})_\mu$ from the value (7) once an expression for $\mathcal{A}^b_{\rm CPT}$ is known in terms of $\overline{{\rm Im}\,\xi_s}$. To derive this relationship for $\mathcal{A}^b_{\rm CPT}$, we note that

$$\mathcal{A}^b_{\rm CPT} = \frac{R^- - R^+}{R^- + R^+}, \tag{9}$$

where $R^\pm$ represents the number of right-sign decays into $\mu^\pm X$. As measured at D0, these quantities are a sum over contributions from the $B^0_d$-$\overline{B}^0_d$ system, from the $B^0_s$-$\overline{B}^0_s$ system, and from all other $b$ hadrons. Labeling these three sources as $q = d,\ s,\ u$ and using an overbar to identify quantities for the $b$ quark, we can write [18]

$$\begin{aligned} R^+ &= f_d T_d \Gamma^{\rm sl}_d + f_s T_s \Gamma^{\rm sl}_s + f_u T_u \Gamma^{\rm sl}_u, \\ R^- &= \overline{f}_d \overline{T}_d \overline{\Gamma}^{\rm sl}_d + \overline{f}_s \overline{T}_s \overline{\Gamma}^{\rm sl}_s + \overline{f}_u \overline{T}_u \overline{\Gamma}^{\rm sl}_u, \end{aligned} \tag{10}$$

where we denote the production fractions as $f_q$, the time-integrated probabilities for $B \to B$, $\overline{B} \to \overline{B}$, or direct decay of nonmixing states as $T_q$, and the semileptonic decay rates as $\Gamma^{\rm sl}_q$.

Taking for definiteness zero direct T and CPT violation in semileptonic decays, we have $\overline{\Gamma}^{\rm sl}_q = \Gamma^{\rm sl}_q$. It is also a reasonable approximation to take $\Gamma^{\rm sl}_d = \Gamma^{\rm sl}_s = \Gamma^{\rm sl}_u$. Symmetric production implies $\overline{f}_q = f_q$, while $f_u = 1 - f_d - f_s$. The absence of mixing for $q = u$ implies $T_u = 1/\Gamma_u$, where $\Gamma_u$ is the total decay rate for the nonmixing $b$ hadrons, which include the $B^\pm$ mesons and the $b$ baryons.

The time-dependent mixing and decay probabilities for neutral $B$ mesons in the $w\xi$ formalism are given explicitly as Eq. (19) of Ref. [15]. These can be integrated over all time $t$ to yield $T_d$ and $T_s$.

For simplicity, suppose the only source of CPT violation comes from $B_s^0$-$\overline{B}_s^0$ mixing. Then, integrating the probability for $B_d^0 \to B_d^0$ over all time $t$ gives $T_d = z_{d+}/2\Gamma_d$, while the integration for $B_s^0 \to B_s^0$ yields

$$T_s = \frac{1}{2\Gamma_s}(z_{s+} + 2z_{s-}x_s\overline{\mathrm{Im}\,\xi_s} + z_{s-}z_{s0}(\overline{\mathrm{Im}\,\xi_s})^2). \quad (11)$$

In these equations, we define

$$z_{q\pm} = \frac{1}{(1-y_q^2)} \pm \frac{1}{(1+x_q^2)}, \quad z_{q0} = (x_q^2 + y_q^2)/y_q^2. \quad (12)$$

Applying CPT gives the additional relations $\overline{T}_d = T_d$ and $\overline{T}_s = T_s(\xi_s \to -\xi_s)$.

Collecting the results, we finally obtain the CPT asymmetry

$$\mathcal{A}^b_{\mathrm{CPT}} = \frac{2f_s z_{s-}x_s\overline{\mathrm{Im}\,\xi_s}}{f_d z_{d+} + f_s z_{s+} + 2f_u + f_s z_{s-}z_{s0}(\overline{\mathrm{Im}\,\xi_s})^2}. \quad (13)$$

We remark in passing that the form of this result for $\mathcal{A}^b_{\mathrm{CPT}}$ holds also in the unaveraged case, provided Eq. (8) is replaced with the complete expression for $\mathrm{Im}\,\xi_s(T, \vec{p}, (\Delta a^{B_s})_\mu)$ and the reasonable approximation is made that the decays occur over times $t$ negligible compared to the sidereal variation with $T$.

To match the theoretical expression (13) to the result (7) obtained from the D0 experiment, we adopt the values $x_d = 0.774 \pm 0.008$, $y_d = 0$, $x_s = 26.2 \pm 0.5$, $y_s = 0.046 \pm 0.027$, $f_d = 0.323 \pm 0.037$, and $f_s = 0.118 \pm 0.015$ [2, 23]. Inverting the expression (13) yields

$$\overline{\mathrm{Im}\,\xi_s} = (2.3 \pm 1.7) \times 10^{-3}. \quad (14)$$

We can also extract the desired measurement of the SME coefficient $(\Delta a^{B_s})_T$ for CPT violation, which is

$$(\Delta a^{B_s})_T = (3.7 \pm 3.8) \times 10^{-12}\ \mathrm{GeV}, \quad (15)$$

where $\Gamma_s = (4.47 \pm 0.08) \times 10^{-13}$ GeV [23]. This corresponds to the bound

$$-3.8 \times 10^{-12} < (\Delta a^{B_s})_T < 1.1 \times 10^{-11} \quad (16)$$

at the 95% confidence level.

The value (15) represents the first sensitivity to CPT violation in the $B_s^0$-$\overline{B}_s^0$ system. The result (14) for $\mathrm{Im}\,\xi_s$ is consistent with no effect at 1.4 standard deviations, which is a reasonable result given the size of the systematic errors in the basic D0 asymmetry (2) and the SM-corrected asymmetry (7). The fractional error on the coefficient $(\Delta a^{B_s})_T$ for CPT violation is greater, due primarily to the comparatively large uncertainty in the value of $y_s$.

For the D0 study of CPT-invariant CP violation, the signal of 3.2 standard deviations was obtained by reducing the systematics on $A^b_{\mathrm{sl}}$ by combining the result (2) with an independent measurement of $a^s_{\mathrm{sl}}$. We observe here that a similar technique could be used in the present context of CPT violation. The basic idea is to reduce the systematics by combining the result (2) for $A^b_{\mathrm{sl}}$ with an independent measurement of CPT violation. The relevant quantity for the latter measurement is the asymmetry $\mathcal{A}^b_{\mathrm{CPT}}$ for inclusive 'right-charge' muon semileptonic decays defined in Eq. (5). The overall CPT reach including the result (15) might be substantially sharpened via this method. However, extracting the asymmetry $\mathcal{A}^b_{\mathrm{CPT}}$ requires access to the full D0 dataset and hence lies outside our scope.

For a neutral meson containing valence quark $q_1$ and antiquark $q_2$, the observable $\Delta a_\mu$ is given by $\Delta a_\mu \approx r_{q_1}a^{q_1}_\mu - r_{q_2}a^{q_2}_\mu$. The coefficients $a^{q_1}_\mu$, $a^{q_2}_\mu$ appear in the SME Lagrange density in terms of the form $-a^q_\mu \overline{q}\gamma^\mu q$ for each quark $q$, while $r_{q_1}$ and $r_{q_2}$ are quantities of order one arising from quark-binding and normalization effects [3]. The value of $\Delta a_\mu$ is then primarily determined by the heaviest valence quark. Note this implies that the zero-sum rule

$$(\Delta a^K)_\mu - (\Delta a^{B_d})_\mu + (\Delta a^{B_s})_\mu \approx 0 \quad (17)$$

holds to a good approximation.

For $B_d^0$-$\overline{B}_d^0$ mixing, the BaBar Collaboration has obtained the measurement [13]

$$\begin{aligned}(\Delta a^{B_d})_T - 0.30(\Delta a^{B_d})_Z &= \\ &(-3.0 \pm 2.4) \times 10^{-15}(\Delta m_d/\Delta\Gamma_d)\ \mathrm{GeV}. \quad (18)\end{aligned}$$

The ratio $\Delta m_d/\Delta\Gamma_d \gtrsim 10.6$ in this case [23], so this measurement is compatible with the result (15) and the zero-sum rule (17). For the $D^0$-$\overline{D}^0$ system, the FOCUS Collaboration has obtained the measurement [12]

$$\begin{aligned}(\Delta a^D)_T - 0.60(\Delta a^D)_Z &= \\ &(1.8 \pm 3.0) \times 10^{-16}(\Delta m_D/\Delta\Gamma_D)\ \mathrm{GeV}. \quad (19)\end{aligned}$$

The ratio $\Delta m_D/\Delta\Gamma_D \simeq 0.6$ is smaller here, yielding an improved sensitivity [23], albeit to effects involving other quark flavors and SME coefficients. Several results have also been obtained for the $K^0$-$\overline{K}^0$ system. By studying different processes, the KLOE Collaboration has obtained the independent measurements [11]

$$\begin{aligned}(\Delta a^K)_T &= (0.4 \pm 1.8) \times 10^{-17}\ \mathrm{GeV}, \\ (\Delta a^K)_Z &= (2.4 \pm 9.7) \times 10^{-18}\ \mathrm{GeV}. \quad (20)\end{aligned}$$

Using data from the Fermilab E773 experiment [24], a constraint of

$$|(\Delta a^K)_T - 0.60(\Delta a^K)_Z| \lesssim 5 \times 10^{-21}\ \mathrm{GeV} \quad (21)$$

has also been obtained [21]. These values are all compatible with the result (15) and the zero-sum rule (17).

More general analyses of the D0 data could in principle be countenanced. Given sufficient statistics and a good understanding of the spectrum, the spatial coefficients $(\Delta a^{B_s})_J$ for CPT violation could be measured and disentangled by combining a search for sidereal variations with spectral analysis. Sidereal sensitivities have already been obtained by KTeV [10], KLOE [11], FOCUS [12], and BaBar [13]. All the sidereal results are compatible with the result (15).

Another option for future investigation is to allow for nonzero contributions from $\mathrm{Im}\,\xi_d$ in the $B_d^0$-$\overline{B}_d^0$ system simultaneously with ones from $\mathrm{Im}\,\xi_s$. This requires a nonzero value of $y_d$. With both effects present, and averaging over 4-momentum and sidereal time as before, the asymmetry (13) acquires a term in the numerator proportional to $\overline{\mathrm{Im}\,\xi_d}$, while the denominator contains an additional term proportional to $(\overline{\mathrm{Im}\,\xi_d})^2$. This analysis would therefore yield a constraint involving both $(\Delta a^{B_d})_T$ and $(\Delta a^{B_s})_T$, albeit with a large error due to the current uncertainty in the value of $y_d$. A global fit of this type could also combine data from different experiments for the $B_d^0$-$\overline{B}_d^0$ and $B_s^0$-$\overline{B}_s^0$ systems. Ideally, information from $K^0$-$\overline{K}^0$ experiments would be incorporated via Eq. (17) to extend further the CPT reach.

Analyses along these lines are also well suited to other ongoing experiments investigating neutral mesons. Searches with high statistics and high boost, such as those feasible at the LHCb experiment [25] with average boost factor $\overline{\gamma} \simeq$ 15-20, offer the capability to study CPT violation in $B$ mesons with sensitivities unattained to date. The results presented here outline a potential window for the exploration of physics beyond the SM and can serve as an impetus for future studies of CPT violation.

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